UNIT-1 PECD

FUNDAMENTALS OF ELECTRIC DRIVES

* Discussed topics:-

→ Block diagram electric drive
→ Fundamental torque equation
→ Load torque components
→ Nature & classifications of load torque
→ Study state stability
→ Load equalisation.
→ Four quadrant Operation of DC drive.
→ Braking methods.

* Block diagram of Electric drive:-

The drives which employ electrical motors at the movers are called electric drives. Electrical drives find a wide range of applications in fans, humonoids, industrial systems, machine tools, etc.

The block diagram of an electric drive is shown in figure below, it has following parts.

1. Source 2. Power modulation
3. Electrical motors 4. Sensing unit

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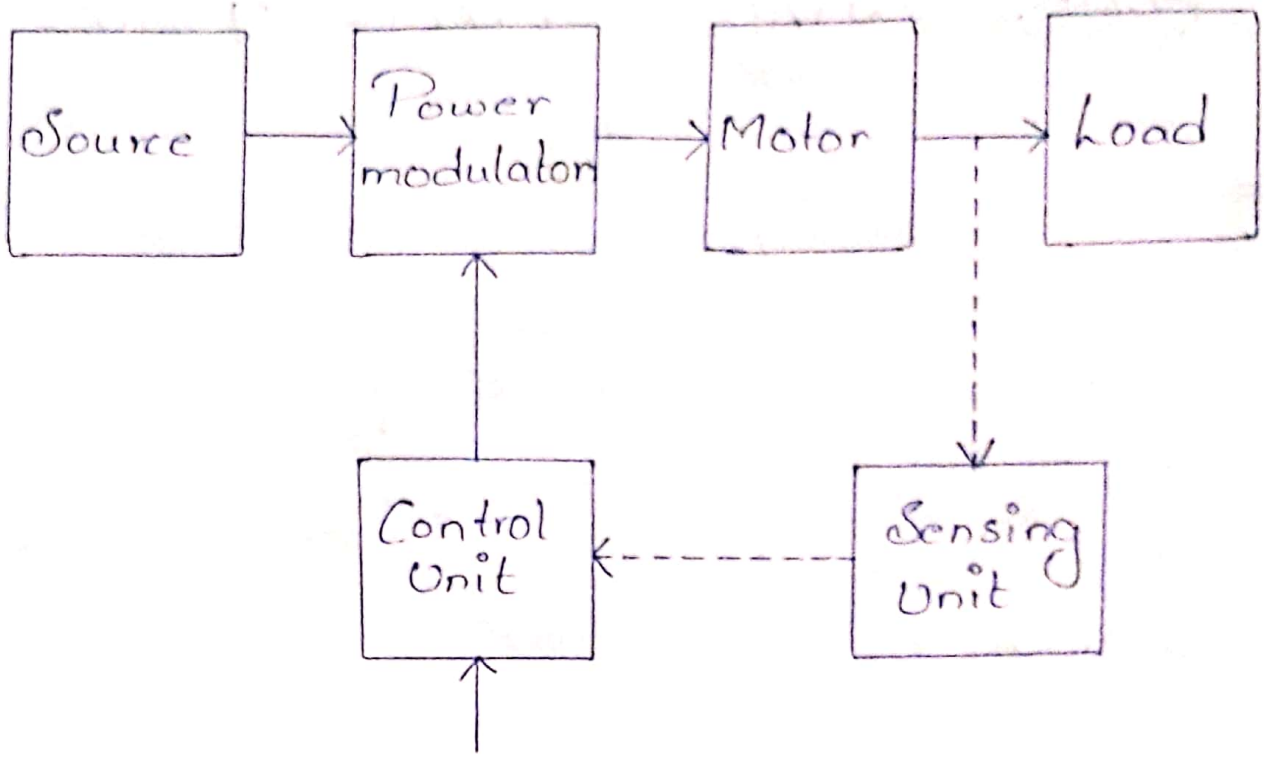
5. Control unit.



1. Source :- Source supplies power to the entire drive. It is of two types.

(i) DC Source

(ii) AC Source

(i) D.C Source :- DC source loads like fork lift truck, depending upon the size of battery typical values of voltages are 6V, 12V, 24V, 48V, etc.,

(ii) A.C source :- For low power ratings 1-ϕ 50Hz supply is used and for high power ratings 3-ϕ 50Hz, 3.3 KV, 6.6 KV, 11KV supply

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is used though fraction have high power ratings, 1-ϕ 50Hz is employed in it because of reduced cost of clearance, for low and medium power motors 400V supply is used.

2. Power Modulator:-

It modulates the input power from the source according to the requirment of the load. the most commonly used power modulators are, (i) converters:- a) AC to DC converters (b) AC voltage controllers (c) choppers (or) DC to DC converters (d) Inverters (or) DC to AC converters (e) cyclo converters.

the following are the main function of the power modulator.

→ To modulate the power flow from the source to the motor

→ To convert AC to DC (or) DC to AC

→ To select either motoring or braking mode of operation of motor.

3. Electrical motors:- Most commonly used electrical motors are,

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(i) DC motors:- shunt, Series, Compound & Permanent magnet motors.

(ii) Brush less DC motors, Stepper motors, Switched reluctance motor.

4. Sensing unit:-

Sensing unit sensors the output of the load currents it into the signal that can be understood by the Control unit. Generally two types of Sensors.

(1) Speed Sensors (2) Current sensors

5. Control unit:-

The controls for the power modulator are provided into the control unit the nature of the control unit for a particular drives depends on the power modulator that is used.

* Fundamental torque equation:-

In fundamental torque equation, usually electric motor drive is connected to the load which has rotational motion.

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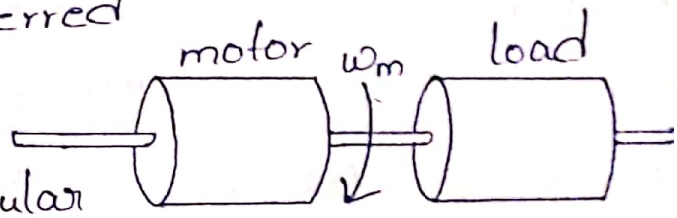
The speed of the motor may not be same as that of load. Thus it is desira-ble to represent the motor load system by an equivalent rotational system shown in figure.

Let,

J - Polar moment of inertia of motor load referred to motor shaft (



ω_m - Instantaneous angular velocity of motor (rad/sec)

T - Instantaneous value of developed motor torque (N-m)

Now, from the fundamental torque equatio

$$T - T_l = \frac{d}{dt}(J\omega_m)$$

$$T - T_l = J\frac{d\omega_m}{dt} + \omega_m \frac{dJ}{dt} \quad \text{—— (1)}$$

For constant inertia drives, we have

$$\frac{dJ}{dt} = 0 \quad \text{—— (2)}$$

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sub eqn (2) in eqn (1), we have

$$T - T_l = J\frac{d\omega_m}{dt}$$

$$T = T_l + J\frac{d\omega_m}{dt} \quad \text{——— (3)}$$

from eqn (3), it can be seen that the motor torque balanced by the load torque and dynamic torque. so this equation helps in determing the drive operating point.

* Load torque Components:-

The following are the three different components of load torque.

(i) Friction torque:-

The torque which is produced by friction forces and opposes rotational motion is known as friction torque it is denoted by T_f.

friction torque,

$$T_f = T_v + T_c + T_s \quad \text{——— (1)}$$

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where,

T_V = Viscous friction torque

T_c = Coloumb friction torque

T_s = additional torque at stand still.

we know that,

Viscous friction torque,

$$T_V = B\omega_m \quad \text{——} \quad (2)$$

T_s can be neglected in dynamic analysis as it is present only at stand still.

Now, sub eqn (2) in eq (1), we get,

$$T_f = B\omega_m + T_c$$

(ii) Windage torque :-

The torque produced by wind opposing the direction of rotation of motor during its operation is called windage torque. It is denoted by T_w.

(iii) Torque required to do Useful mechanical work :-

The nature of this torque depends

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on particular operation.

i.e,

→ it may be constant

→ it may vary with time

→ it may vary with speed

→ it may also vary with load.

* Nature & Classification of load torque:-

The nature of load torque depends on particular application the speed torque characterstics of given drive may not be same as that of load. Different types of loads exhibit different speed torque characterstics. However most of the industrail loads are classified into following four categorics.

(i) constant torque load i.e., $T = K$

(ii) Torque proportional to speed i.e, $T \propto N$

(iii) Torque proportional to square of the speed i.e, $T \propto N^2$

(iv) Torque inversly proportional to speed i.e, $T \propto \frac{1}{N}$

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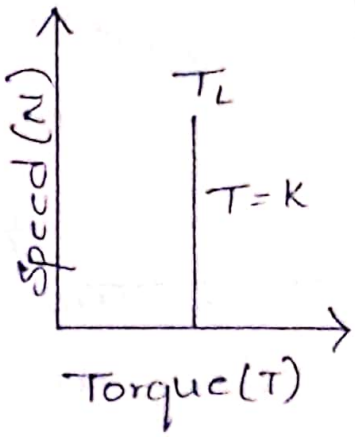
(i) Constant torque type load:-

Fig shows this type of speed-torque characterstics.

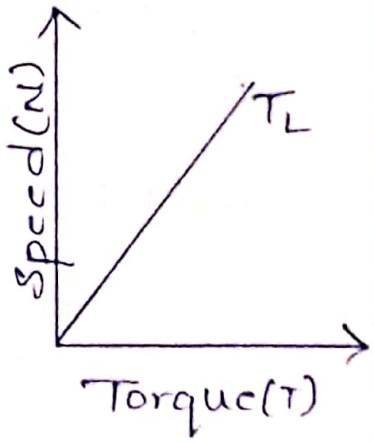
Cranes during hoisting and cranes. exhibits this type of characterstics.



(ii) Torque proportional to Speed:-

Fig shows this type of speed-torque characterstics.

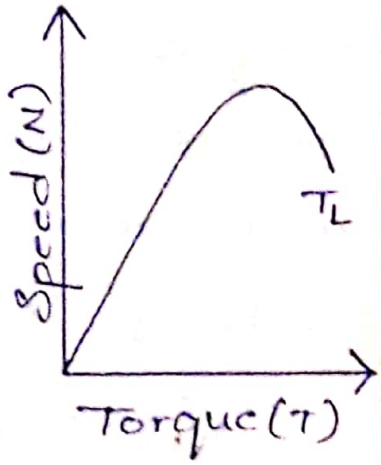
Seperatly excited DC generators connected to constant load resistance exhibit this type of characterstics.



(iii) Torque proportional to Square of speed:-

Fig shows this type of speed-torque characterstics.

Fans, rotatory pumps, Campressors and ship proportional exhibit this type of character-stics.



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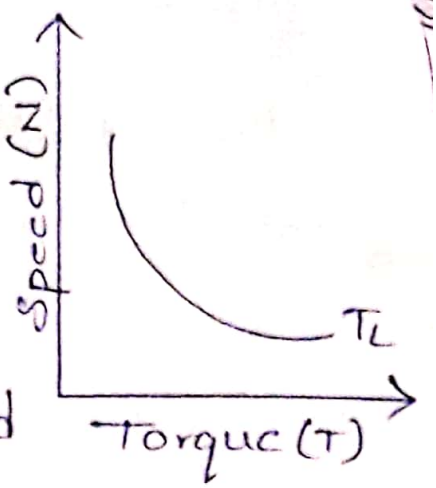
(iv) Torque inversly proportional to speed:-

Fig shows this type of speed-torque characterstics.



Lathe boring machines, milling machines, fraction load etc., exhibit this type of characterstics.

Classification of load torque:-

Load torque are classified into two types. They are

(i) Active load torque.

(ii) Passive load torque.

(i) Active load torque:-

Active load torque are the load torque which have the capability to drive the motor under equilibrium conditions and maintain the sign even if the direction of rotation of drives is reversed.

Ex:- Torque due to gravitational force, tension, compression and torsion.

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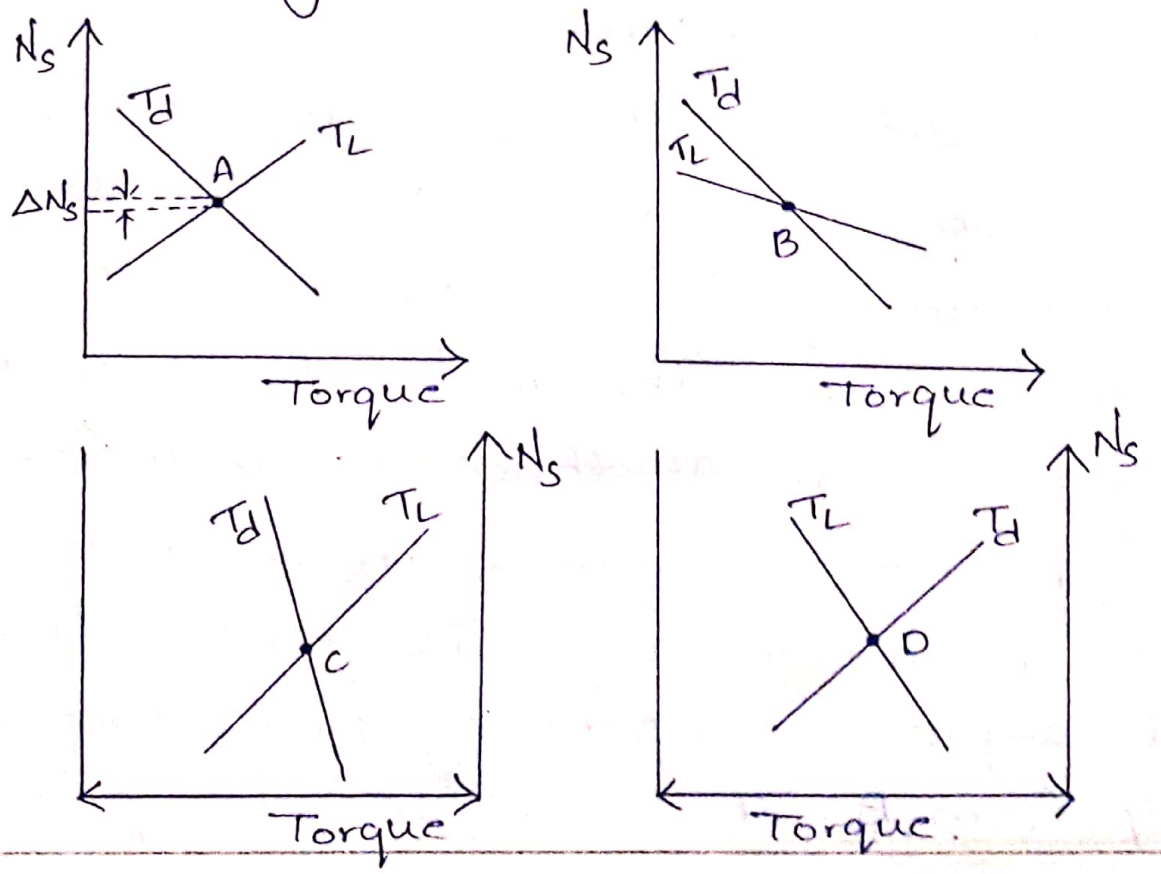
(ii) Passive load torque:-

Passive load torque are the load torque which always resist the motion & change their sign when the direction of rotation of drive is reversed.

Ex:- Torque due to friction, windage, cutting etc.,

* Steady state stability:-

The steady state stability can be explanned by using typical speed-torque characterstics of motor and load as shown in figure.



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let us consider the steady state stability of a drive at an equilibrium point A as shown in figure. The point A will be static only when the operation of motor is restored after a small discharge from it due to a disturbance at motor and load. which results in reduction of speed (ΔN_s). At this resultant speed, the motor torque is greater than the load torque, thus motor get accelerate and operation is restored to A. Again with increase in speed (N_s) due to disturbance the load torque becomes greater than motor torque resulting in deacceleration as well as restoration of operation at point A.

Therefore the drive is steady state stable at point A. Now, let us consider an equilibrium point B which is determined when the motor drives with different load. At this point B motor is working with an increase in speed due to which the motor torque is greater than load torque and operating point moves away from B. Thus B is unstable point of

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equilibrium. Similarly at points C & D the stability of drives can be studied. Following the reasening given for point A, the Operation at point C is stable and D is unstable by given same reasening at point B.

From this above discussion, it can be concluded that the drive is stable when an increase in speed causes load.

* Load equalization :-

In many industrial applications the load fluctuater vary widely within short intervals of time. Electric hammers, presses, reciprocating pumps etc.,

For increasing load.

let the load for this condi-tion is increasing or is the peak load. The speed will then decreases due to which the fly wheel will give out some energy 'E'. Therefore under this condition.

$$T_m = T_L - T_F \quad \text{——— (1)}$$

$$\text{Energy} = \frac{1}{2} mv^2$$

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$$= \frac{1}{2} J (\omega_0^2 - \omega^2)$$

$$= \frac{1}{2} J (\omega_0 + \omega)(\omega_0 - \omega)$$

$$= J \left[\frac{\omega_0 + \omega}{2}\right](\omega_0 - \omega)$$

$$= Js \left[\frac{\omega_0 + \omega}{2}\right]$$

$$= Js\omega$$

T_m = motor torque

T_L = load torque

T_f = flywheel torque

ω_0 = No load speed

ω = full load speed

Power Output $= \frac{d}{dt} Js\omega$

$$P = j\omega \frac{ds}{dt}$$

$$\text{Power} = \frac{2\pi NT}{60} \Rightarrow P = \frac{2\pi NT}{60}$$

$$T = \frac{60 \times P}{2\pi N}$$ Here 2π & 60 are constants

$$T = \frac{P}{N}$$

flywheel torque $T_F = \frac{P}{\omega}$

$$= \frac{j\cancel{\omega}\, ds/dt}{\cancel{\omega}}$$

$$T_F = J\frac{ds}{dt}$$

from eqn (1)

$$T_m = T_L - T_F$$

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$$T_m = T_L - j\frac{ds}{dt}$$

s is very low, $s = KT_m$

$$T_m = T_L - j\frac{d}{dt} KT_m$$

$$T_m = T_L - jK\frac{dT_m}{dt}$$

$$JK\frac{dT_m}{dt} = T_L - T_m$$

$$JK\,dT_m = (T_L - T_m)\,dt$$

$$\Rightarrow \frac{dt}{JK} = \frac{dT_m}{T_L - T_m} \quad \text{——— (3)}$$

By applying integration.

$$\int \frac{dt}{JK} = \int \frac{dT_m}{T_L - T_m}$$

$$\Rightarrow \frac{1}{JK}\int dt = -\log(T_L - T_m)$$

$$\Rightarrow \frac{1}{jK} t + c = -\log(T_L - T_m) \quad \text{——— (4)}$$

$t = 0$, $T_m = T_0$

$$\Rightarrow c = -\log(T_L - T_0) \quad \text{——— (5)}$$

$$\frac{1}{JK} t - \log(T_L - T_0) = -\log(T_L - T_m)$$

$$-\frac{1}{JK} t = \log(T_L - T_m) - \log(T_L - T_0)$$

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$$-\frac{1}{JK}t = \log\left[\frac{T_L - T_m}{T_L - T_0}\right]$$

Apply antilog on both sides.

$$e^{-1/jk^t} = \left[\frac{T_L - T_m}{T_L - T_0}\right]$$

$$e^{-t/jk}(T_L - T_0) = T_L - T_m$$

$$T_m = T_L - e^{-t/jk}(T_L - T_0)$$

the torque developed by motor due to increase in load condition

$$T_m = T_L - (T_L - T_0)e^{-t/jk}.$$

for load decreasing

$$T_m = T_L + (T_L - T_0)e^{-t/jk}$$

where,

J = moment of inertia

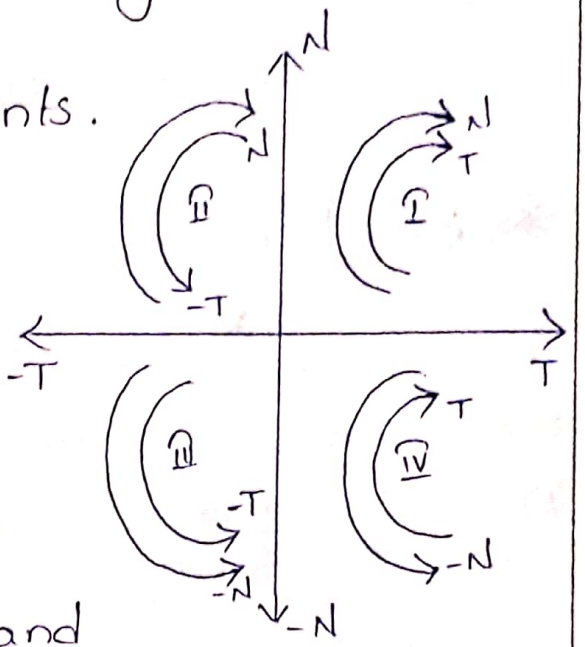
K = proportional constant.

* Four-Quadrant Operation:-

A four quadrant operation is nothing but functioning of the drive in all the four quadrants, the operation where in a drive is required to operate in both directions of rotation is called four quadrant

Operation. The Operation of the four quadrant is shown in figure.

→ If the motor is rotating clockwise direction its Operation is 1 & 2 quadrants.



→ If the motor is rotating anticlockwise direction its Operation is 3rd & 4th quadrants.

→ In the 1st and 3rd quadrants both torque and speed are in some direction.

→ In the 2nd and 4th quadrant, the torque is opposing motion and there operation is called electric braking.

→ In this DC machine is considered 4-quadrants Operation generally seperatly excited machine is used.

These foure Quadrants are.

→ First Quadrant Operation is called forward motoring.

→ Second Quadrant Operation is called forward braking.

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→ Third Quadrant Operation is called reverse motoring.

→ Fourth Quadrant Operation is called reverse braking.

* **Braking:** In any semiconductor device, it is very important to brake or stop the motor and its work for a reasonable short period of time.

Generally braking systems are two types.

(i) Mechanical braking

(ii) Electrical braking.

(i) **Mechanical braking:** -

In this type of braking, the motor is stopped by using a brake shoe or band on a brake drum. it requires frequent maintenance and replacement of brake shoe, and braking power is wasted as well as it dissipates more heat energy, in spite of disadvantages, mechanical braking is used along with electrical braking to ensure reliable operation of the drive mechanical braking is also used to hold the stand still condition.

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Electrical braking:- It is the process by which a running motor can be brought to rest smooth braking of the motors can be achieved by the electrical braking it uses the electric current or magnetic actuating force to reduce the speed of the rotating device.

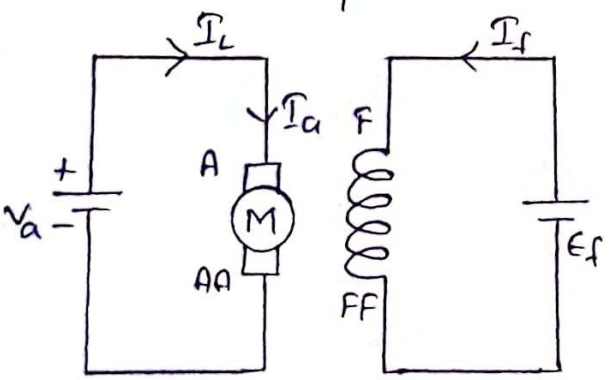
It is classified into three types.

(1) Plugging
(2) Dynamic braking
(3) Regenerative braking.

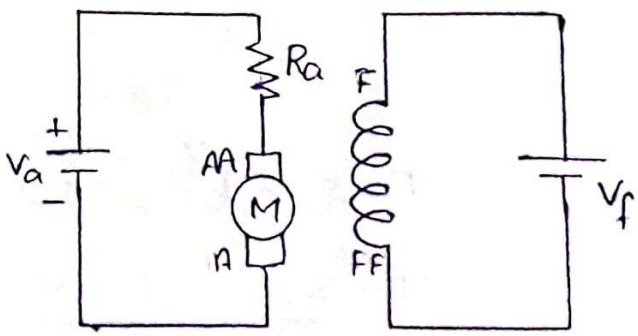
(1) Plugging:- An plugging operation, the armature terminals are reversed, with respect to the field terminals, so that armature current reverses. During normal operation the back emf and the armature voltage are reverse direction but in plugging operation both the back emf and the armature voltage are in same direction.

Seperatly Excited

Normal Operation.

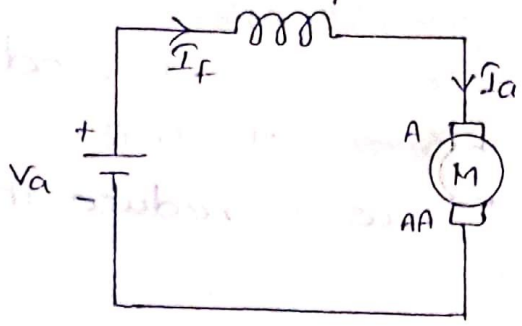


Plugging

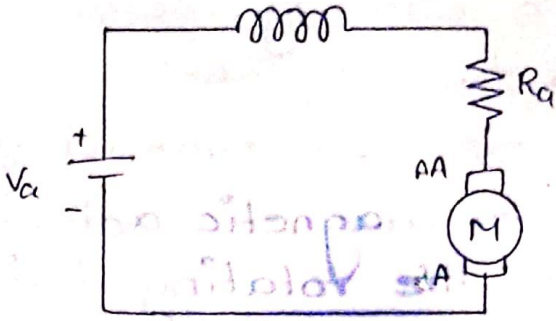


DC Series motor:-

Normal Operation

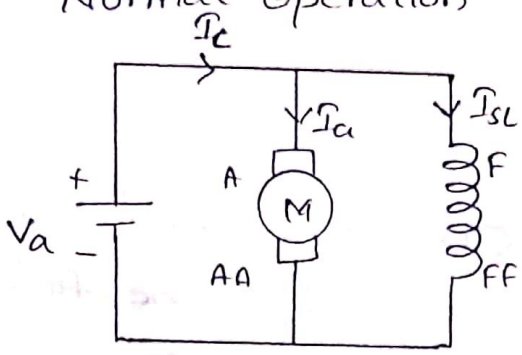


Plugging

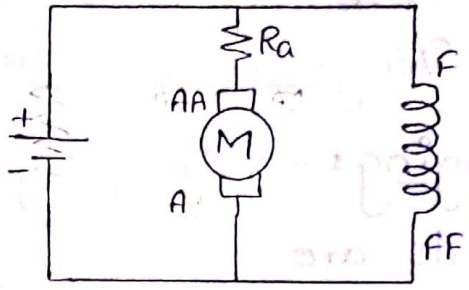


DC Shunt motor:-

Normal Operation



Plugging



In normal operation E_a & E_b are in opposite direction.

In plugging E_a & E_b are in same direction.

we know: $T \propto \phi I_a$

$$T = K_1 \phi I_a$$

Here, $I_a = \frac{V}{R}$

$$= \frac{E_a + E_b}{R_B}$$

$$T = K_1 \phi \left(\frac{E_a + E_b}{R_B}\right)$$

$$T = \frac{K_1 \phi E_a + K_1 \phi E_b}{R_B}$$

$$T = \frac{K_1 \phi E_a}{R_B} + \frac{K_1 \phi E_b}{R_B}$$

Here $E_b \propto \phi N \Rightarrow E_b = K_2 \phi N$

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$$T = \frac{K_1 \phi E_a}{R_B} + \frac{K_1 K_2 \phi^2 N}{R_B}$$

$$T = K_3 \phi + K_4 \phi^2 N$$

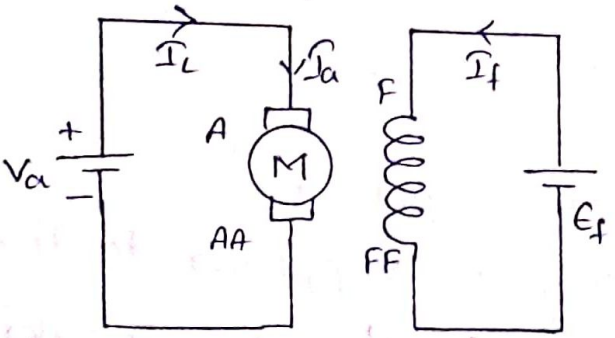
In series motor $\phi \propto I$ $\quad T = K_3 I + K_4 I^2 N$

In shunt motor $\phi \propto$ constant $\quad T = K_3 + K_4 N$.

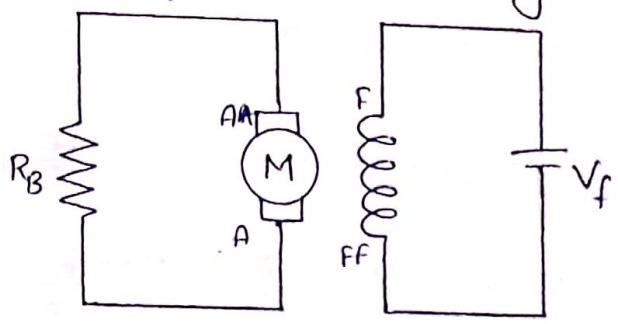
(2) **Dynamic braking:-** In this braking the motor armature terminals is disconnected from the source and it is connected with external resistance R_B across the motor terminals, the kinetic energy is converted into electrical energy and acts as a generator and wasted energy is disipated in resistance R_B. The dynamic braking can be performed both in seperatly and series motors.

Seperatly excited:-

Normal Operation

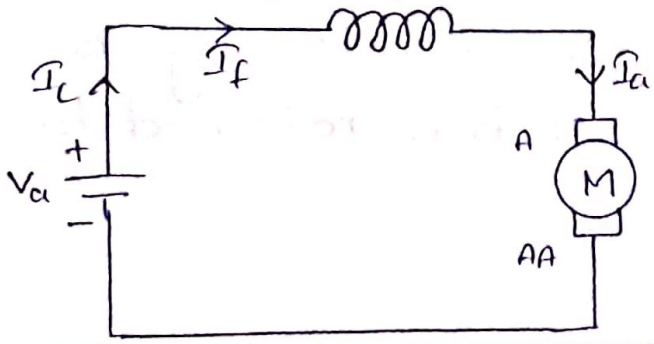


Dynamic braking

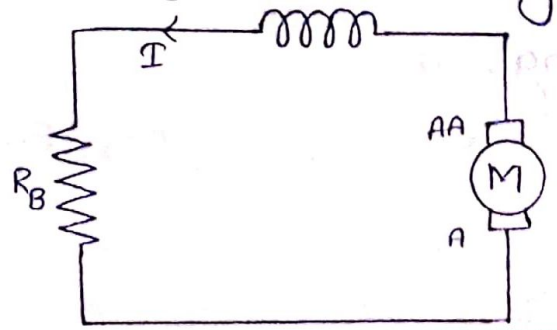


DC series motor:-

Normal Operation



Dynamic braking



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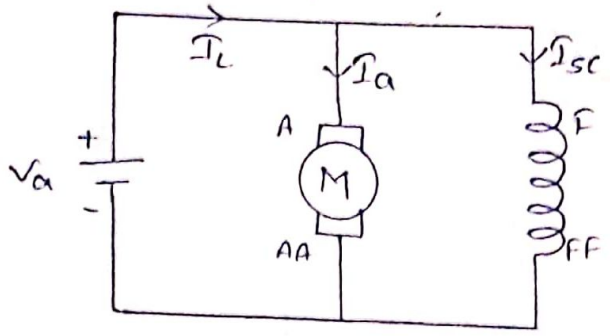
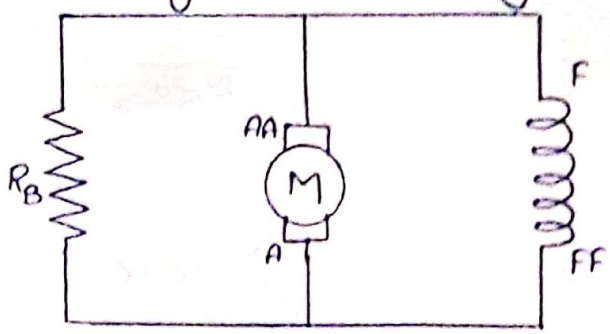
Dc shunt motor

Normal Operation



Dynamic braking



$$T \propto \phi I_a \Rightarrow T = K_1 \phi I_a$$

$$I_a = \frac{V}{R} = \frac{E_b}{R_B}$$

$$T = K_1 \phi \left[\frac{E_b}{R_B}\right]$$

$$E_b \propto \phi N \Rightarrow E_b = K_2 \phi N$$

$$T = K_1 \phi \left[\frac{K_2 \phi N}{R_B}\right]$$

$$T = \frac{K_1 K_2 \phi^2 N}{R_B}$$

$$T = K_3 \phi^2 N$$

In series $\phi \propto I$ $T = K_3 I^2 N$

In shunt ϕ = constant $T = K_3 N$.

(3) Regenerative braking:- In regenerative braking, the generated energy is supplied to the source. for this, the following conditions should be satisfied. $E_b > E_a$ and I_a is negative. In this braking, the motor is run as generator by the kinetic energy of the load, which is returned to the

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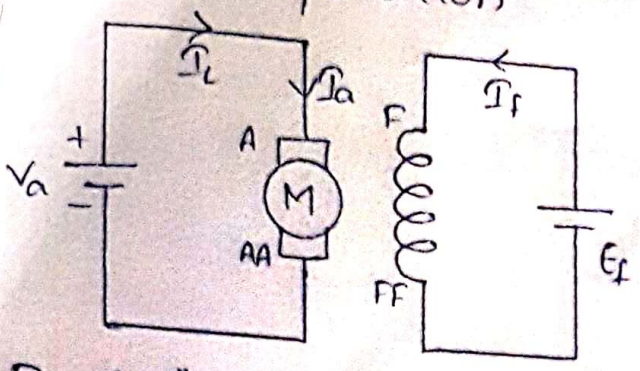
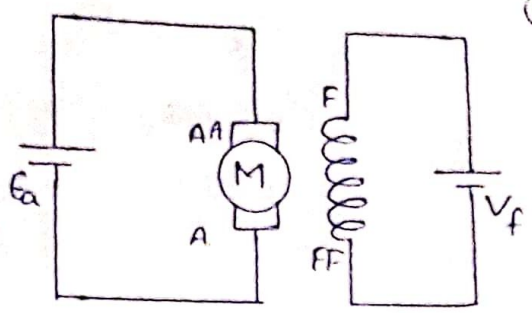
Seperatly excited :-

Normal Operation

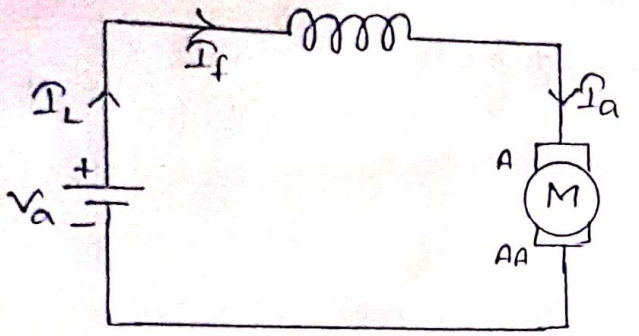


Regenarative braking

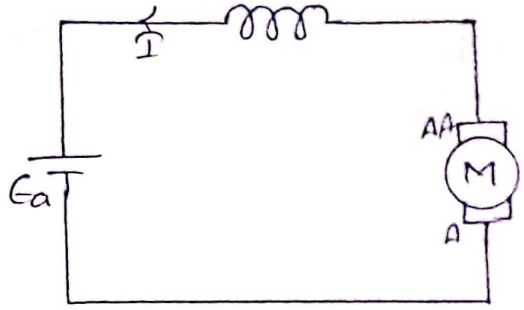


Dc Series motor:-

Normal Operation

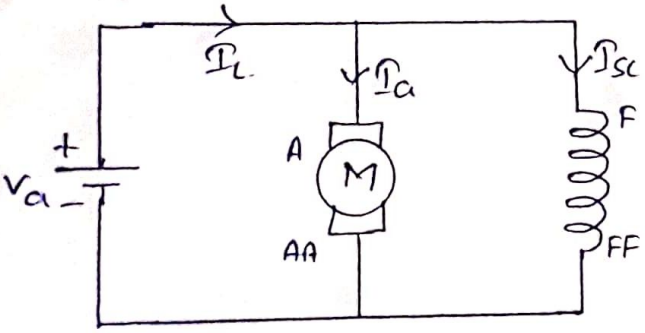


Regenarative braking

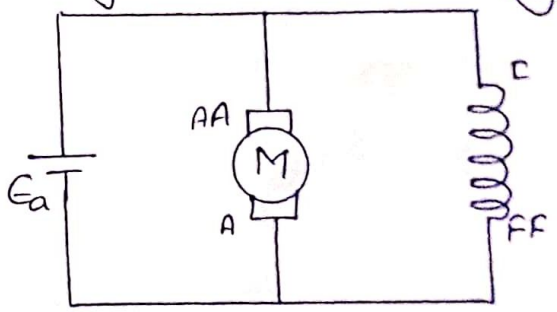


Dc shunt motor:-

Normal Operation



Regenarative braking



$$T \propto \phi I_a \Rightarrow T = k_1 \phi I_a$$

$$I_a = \frac{V}{R}$$

$$I_a = \frac{E_b - E_a}{R_a}$$

$$I_a = -\left[\frac{E_a - E_b}{R_a}\right]$$

$$T = -k_1 \phi \left(\frac{E_a - E_b}{R_a}\right)$$

$$T = \frac{-K_1 \phi E_a}{R_a} + \frac{K_1 \phi E_b}{R_a}$$

$$E_b \propto \phi N$$

$$E_b = K_2 \phi N$$

$$T = -\frac{K_1 \phi E_a}{R_a} + \frac{K_1 K_2 \phi^2 N}{R_a}$$

$$T = -K_3 \phi + K_4 \phi^2 N$$

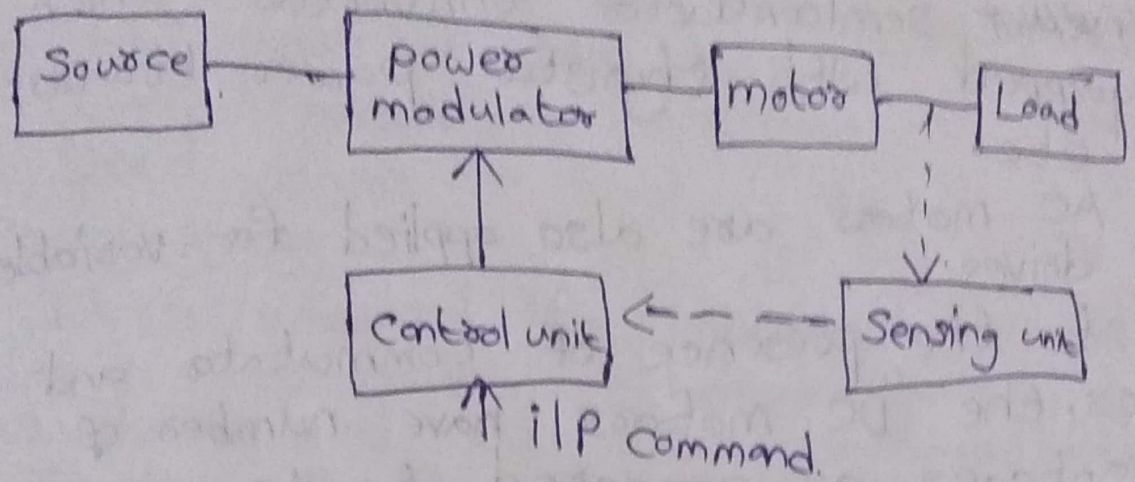
In series $\phi \propto I$ $\quad T = -K_3 I + K_4 I^2 N$

In shunt $\phi \propto$ constant $\quad T = -K_3 + K_4 N$

Unit-V

Fundamentals of electric drive

2.* Block diagram of an electric drive:-



Parts of electric drive:-

1) Electrical motors
2) Power modulator
3) Source
4) Control unit
5) Sensing unit

Electric motors:- Motors which are commonly used for electric drives are DC motors and AC motors.

DC motors.
- series
- shunt
- compound

AC motors
- Induction motors
  - squirrel cage
  - slip ring
- synchronous motor
  - wound field
  - permanent magnet.

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In the past, AC motors were employed mainly for constant speed drives but whereas variable speed drives were dominated by DC motors.
But nowadays due to the development of ~~semi converter~~ semiconductor converters which are equipped with thyristors, power transistors IGBT etc.
The AC motors are also applied for variable speed drives
Due to the presence of commutator and brushes, the DC motors have number of disadvantages as compared to AC motors like high cost, more weight, frequent maintenance, restrictions on maximum voltage, speed and power ratings.
Squirrel cage induction motor cost nearly 1/3rd of a DC motor of the same ratings. is extremely rugged, requires practically low maintenance until we built for high speeds, torques and power ratings.
Wound rotor motors are more expensive than squirrel cage motors.
Because of the advantages of AC drives, in number of variable speed applications DC drives have been replaced with AC drives

Power modulator:-

Cyclo converters, converters, inverters, AC voltage regulators, DC choppers, ~~sou~~

Sources:-

1-ϕ & 3-ϕ AC supply is available, very low power drives are generally fed from a 1-ϕ source and whereas low and medium power motors are fed from 400V supply and for high rating motors may be rated at

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3.3kV, 6.6kV & 11kV.
Some drives are powered from a battery whose voltage may be 24V, 48V & 110V DC

Sensing unit:-
Sensing units are of two types based on the input of the load.
1) Current sensor
2) Speed sensor

Speed sensor:-
It is required for implementation of closed loop control schemes. Speed is usually sensed by using tachometers.
In case of large industries like paper mills, digital tachometers are used.

Current sensor:-
There are two methods of sensing the current.
1) Use of current sensor employing Hall effect
2) Use of non-inductive resistance shunt in conjunction with an isolation amplifier.

Drive:- It is defined as the speed of motion control is called as Drive.
It employes in electric motors is known as electric drive.

Applications:-
Washing machine, fans etc

Advantages:-
1) Flexible control characteristics for steady state
2) Wide speed range control
3) Wide torque range control.
Electric drives has low maintenance, less noisy and provide clean operation
4) The drives can operate in radioactive, contaminated environment, submerge in liquids, Vertical operation and inclined operation.

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Choice of electrical drive:-

1) Steady state requirement:- Four quadrant operation, nature of speed torque characteristics, speed range, speed regulation, electrical braking, ~~transient requirement starting~~

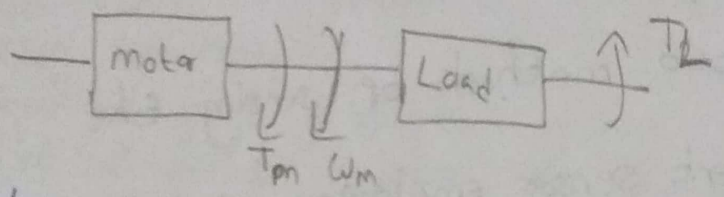
2) Transient requirement:- Starting, speed reversal & electrical braking

3) Type of source:- The voltage fluctuations, power factor, harmonics, capacity of the source etc.

4) Reliability

5) Space and weight availability.

Fundamental torque equation of an electrical drive



*Motor generally drives a load such that the load may go rotational motor or linear motion. The motor developed torque will be in opposite direction to the load torque.

The load has a moment of inertia in transient condition

$$T_m - T_L = \frac{d}{dt}(J \cdot \omega_m)$$

$$T_m = T_L + J\frac{d\omega_m}{dt} + \omega_m \cdot \frac{dJ}{dt}$$

$$\therefore T_m = T_L + J\frac{d\omega_m}{dt} \quad [\because J \text{ is a constant}]$$

where T_m is instantaneous value of a motor developed torque

T_L is the instantaneous value of a load torque and J is moment of inertia of motor and load.

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ω_m is an instantaneous value of angular velocity of a motor as the inertia is constant the term $\omega_m \frac{dJ}{dt} = 0$ but in some applications like robotics, coal winders the inertia is not constant then.

$\longrightarrow \omega_m \frac{dJ}{dt}$ plays a vital role.

* The drive may accelerate or decelerate based on the relation b/w motor torque and load torque.

When motor torque greater than load ~~or~~ torque, the drive will accelerate indicated by a +ve sign.

When $T_m < T_L$, the drive will decelerate (de-accelerate) which is indicated by a -ve sign.

~~When T_m~~

The energy associated with torque due to inertia is stored in the form of kinetic energy and also during acceleration.

When deceleration takes place, the stored kinetic energy is dissipated to the load.

Four quadrant operation of Hoist:- 6.5

There are different modes of operation which are given by

1) Forward motoring mode
2) Forward braking mode
3) Reverse motoring mode
4) Reverse braking mode. ~~as~~ which are given as I, II, III, IV quadrants respectively.

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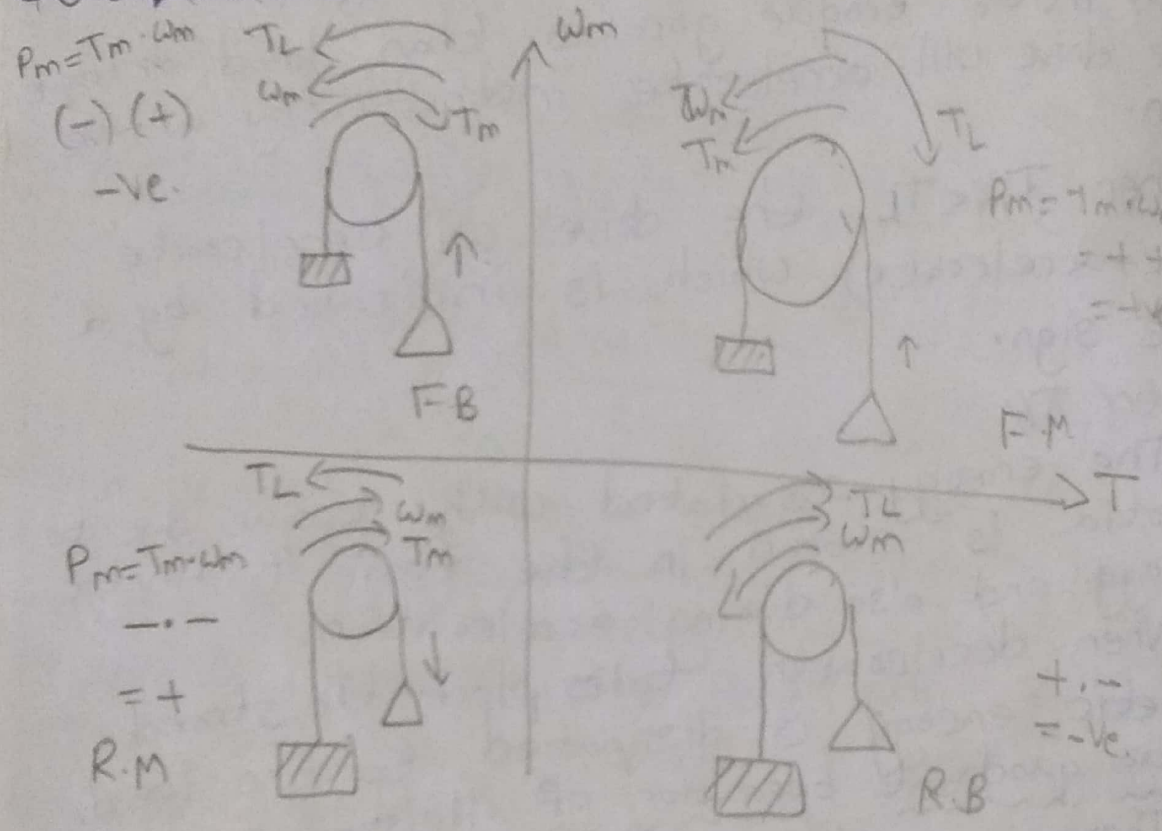
Ist quadrant :-

The torque developed by the motor and speed, both are in same direction but the load torque is in opposite direction to them.

∴ Power produced in the motor.

$P_m = T_m \cdot \omega_m = +ve$. which indicates the power ~~When~~ is flowing from source to load and is known as forward motoring mode.

IInd quadrant :-



IInd quadrant :-

In IInd quadrant i.e forward braking an empty cage is moving up and the counter weight is heavier than the empty cage. In order to limit the speed of empty cage ~~mode~~ motor the produces negative power such that the motor torque is in opposite direction with respect to Ist quadrant.

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IIIrd quadrant

In IIIrd qua i.e the reverse motoring. The power in the third quadrant is positive because the motor torque is negative. and speed is also negative w.r.t first quadrant.

Here empty cage is moving downwards since the weight of empty cage is lesser than the counter weight. To pull the counter weight upwards where motor produces the torque in clockwise direction.

IVth quadrant :-

In IVth qua i.e reverse braking, the loaded cage is moving downwards since the loaded cage weight is more than the counter weight. due to gravity, the speed of the cage will increase.

Therefore, the motor produces a torque in anticlockwise direction.

The power developed in motor is negative. In Ist & IIIrd quadrants the power is +ve which indicates power flow from source to load

In IInd & IVth quadrants the power is -ve which indicates the power flow from load to source.

Load components :-

It can be divided into 3 types.

1) Frictional torque (T_f)

2) Frictional torque is divided into 3 types.

(i) Viscous friction (T_v) torque :-

(ii) This component varies linearly w.r.t speed

$T_v \propto \omega_m$

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(ii) Coulomb frictional torque (T_c) :- This component is independent of speed.

(iii) Static frictional torque (T_s) :- Friction at zero speed or stand still position is called as static friction.

2) Windage torque (T_w) :-

When the motor runs, wind generates a torque which opposes the motor rotation. The windage torque is directly proportional to square of the speed

$$T_m \propto \omega_m^2.$$

3) Useful torque (T_L) :-

It depends upon particular application and it may be constant, independent of speed. Therefore, the motor torque is given by

$$T_m = T_L + J.\frac{d\omega_m}{dt} + T_v + T_w + T_c + T_s$$

$$= T_L + J.\frac{d\omega_m}{dt} + k\omega_m + k\omega_m^2 + T_c$$

3 Steady state stability of an electric drive :-

The equilibrium point of an electrical drive is obtained by mathematical analysis or graphical analysis. The mathematical analysis consists of differential equations which are time taking so the graphical analysis gives a better solution to study equilibrium point.

The equilibrium point for an electric drive is obtained when motor torque is equal to load torque.

The fundamental torque eq is given by

$$T_m - T_L = J.\frac{d\omega_m}{dt} \quad \text{—(1)}$$

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Let us ~~simp~~ consider a small disturbance in motor load. Therefore the changes in motor torque ~~Δt~~ ΔT_m, load torque ΔT_L and change in speed $\Delta \omega_m$

$$\therefore (T_m + \Delta T_m) - (T_L + \Delta T_L) - J \cdot \frac{d}{dt}(\omega_m + \Delta\omega_m) = 0$$

$$T_m - T_L - J \cdot \frac{d\omega_m}{dt} + \Delta T_m - \Delta T_L - J \cdot \frac{d}{dt}(\Delta\omega_m) = 0$$

$$J \cdot \frac{d\omega_m}{dt} - J\frac{d\omega_m}{dt} + \Delta T_m - \Delta T_L - J \cdot \frac{d}{dt}(\Delta\omega_m) = 0$$

$$\Delta T_m = \Delta T_L + J\frac{d}{dt}(\Delta\omega_m) = 0 \quad \text{—} (2)$$

Assume that the speed torque charac of motor at load are straight lines

$\therefore$ The slopes of the st lines are given by

$$\Delta T_m = \frac{dT_m}{d\omega} \cdot \Delta\omega_m \quad \text{—} (3)$$

$$\Delta T_L = \frac{dT_L}{d\omega} \cdot \Delta\omega_m \quad \text{—} (4)$$

Sub (3) & (4) in (2)

$$\frac{dT_m}{d\omega} \cdot \Delta\omega_m - \frac{dT_L}{d\omega} \cdot \Delta\omega_m - J \cdot \frac{d}{dt}(\Delta\omega_m) = 0 \quad \text{—} (5)$$

$$\cancel{J} \cdot \frac{d}{dt}(\Delta\omega_m) = \left(\frac{dT_m}{d\omega} - \frac{dT_L}{d\omega}\right)\Delta\omega_m$$

$$\int J \cdot \frac{d}{dt}[\Delta\omega_m]\, dt = \int \left(\frac{dT_m}{d\omega_m} - \frac{dT_L}{d\omega}\right)\Delta\omega_m\, dt$$

$$\int J \cdot d(\Delta\omega_m) = \int \left(\frac{dT_m}{d\omega} - \frac{dT_L}{d\omega}\right) dt \cdot \Delta\omega_m$$

eq (5) is the first order diff eq by using variable separable method, the soln is given by

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$$\boxed{\Delta\omega = (\Delta\omega_0)\, e^{-\frac{1}{J}\left(\frac{dT_L}{d\omega} - \frac{dT_m}{d\omega}\right)t}}$$

The -ve exponential func indicates that $\Delta\omega \to 0$ but $\frac{dT_L}{d\omega} - \frac{dT_m}{d\omega} > 0$ i.e, the load torque is greater than motor torque.

Nature of the load and classification:

The load depends upon a particular application. A low speed hoist is an example where the torque is independent of speed ∴ The load component to be considered is Coulombs friction. Another example where torque is independent of speed is paper mill drive. Fans, compresses centrifugal pumps ship ~~shipped ft~~ propellers are the examples where load torque is a function of square of speed. ~~It~~ In these applications, windage load component dominates

$T_w \propto T_m \propto \omega_m^2$.

In constant speed applications like rolling machine, milling machine, viscous frictions, load component is dominant then all other torque components.

In traction, the load torque is dependent upon windage, static frictions at standstill condition and then the locomotive moves the ground is not levelled. The train has to move upward and downward directions so additional load component i.e, torque due to gravity is to be considered.

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Active load torque:- Load torques which have a potential to drive the motor to equilibrium position and retain their sign when the direction of drive is changed are called as Active load torque.

Passive load torque:- Load torques which opposes the rotation reversal and sign change are called as passive load torques.

Load equilization:-

In some drive applications, the load fluctuates for a very short interval. For example, the pressing machine, electrical hammer, printing machine, the large torque is ~~appl~~ required for a very short duration otherwise the net torque is zero.

The motor draws very high pulsed current from the supply which gives rise to voltage fluctuations which effects the other loads.

To overcome this problem, a flywheel is assembled on the motor shaft. During high load torque, the motor will be de-accelerated and the kinetic energy will be supplied by the fly wheel. which drives the load.

During light load condition, the speed is increased the flywheel stores the kinetic energy and torque is minimum. By this flywheel system, the fluctuations are reduced which is called as Load equilization.

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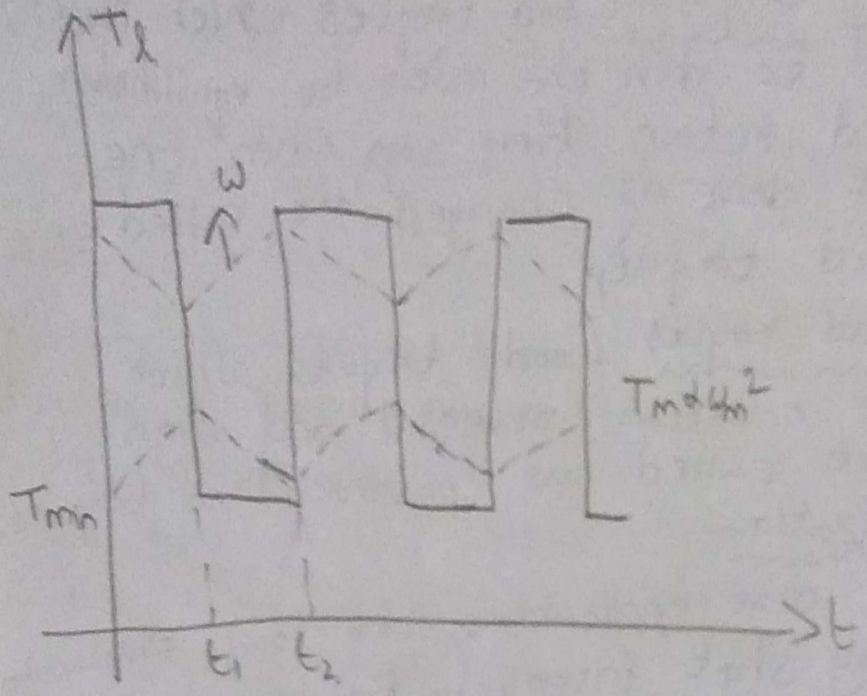


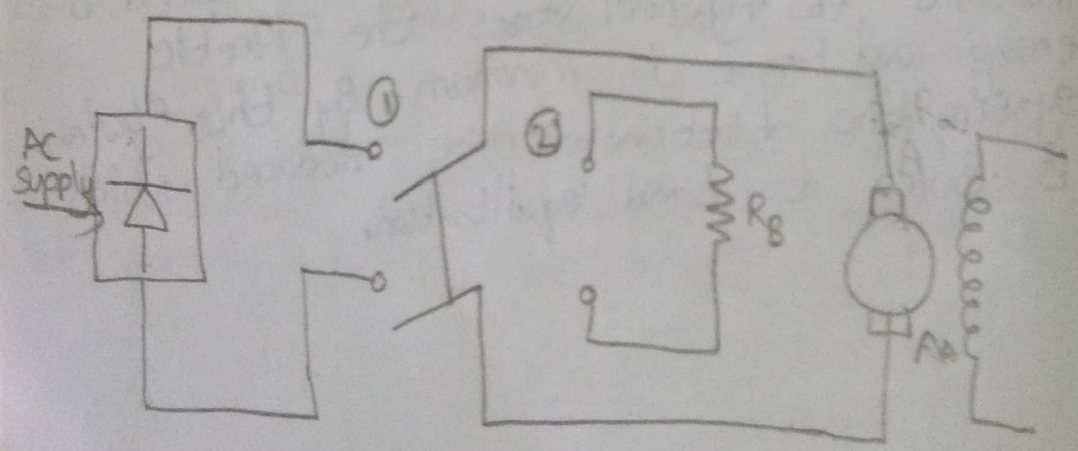
Braking :-

The generating mode of a machine is called as braking where the power is fed from load to source and the electromagnetic torque produced in this mode is in opposite direction to the motor rotation and speed reduces to zero.

Braking is classified into 3 types

1) Rheostatic or dynamic braking
2) Plugging
3) Regenerative braking.

Rheostatic or dynamic braking :-



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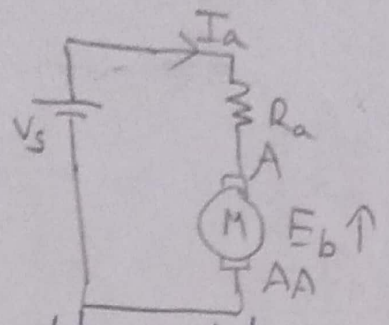
Initially DPST switch is in position 1. Therefore, the machine is working as a motor which drives the load at the speed of ω.

∴ The armature current is given by

$$I_a = \frac{V_s - E_b}{R_a}$$



Now, the switch is thrown on the pos 2 which will disconnect the supply terminals and connects the braking resistance R_b across the armature.

Now the current in armature is reversed and it is coming out from A

Now, $I_A = \frac{E_b}{R_a + R_B}$.

* The DC separately excited motor has an armature resistance of 0.04Ω and the motor is coupled to the load with a torque of 400 N-m drawing a current of 200A. Motor is brake by dynamic braking with a resistance of 1Ω. Calculate (i) speed of motor which holds the load (ii) what should be the braking resistance for keeping the speed at 600 rpm.

Sol) $T \propto \phi I_a$

$T = K \cdot \phi \cdot I_a$

$E_b = \frac{\phi Z N}{60} \times \frac{P}{A}$

$E_b \propto \phi N \Rightarrow E_b = K \cdot \phi N$

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Given,

$R_a = 0.04\Omega$

$I_a = 200A$

$T = 400 N\text{-}m$

$R_B = 1\Omega$

(i) $N = ?$

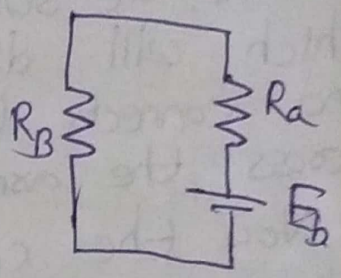
(ii) R_B at $N = 600$ rpm

As $T \propto \phi I_a = K\phi I_a$

$$K\phi = \frac{T}{I_a} = \frac{400}{200} = 2$$

For dynamic braking

$$I_a = \frac{E_b}{R_a + R_b}$$



$$E_b = I_a (R_a + R_b)$$

$$= 200(0.04 + 1) = 208V.$$

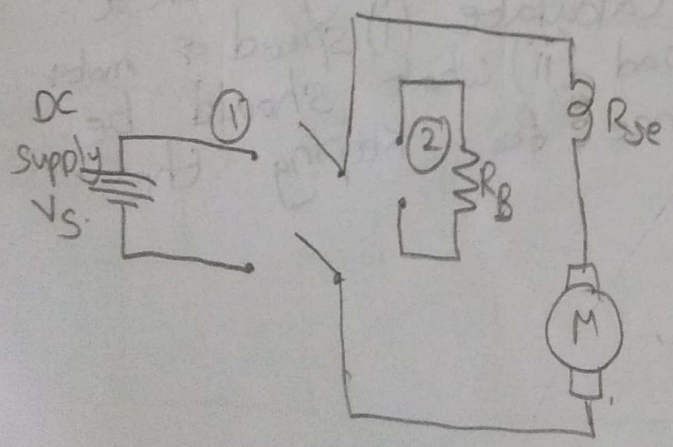
W.K.T,

$$E_b = K\phi N$$

$$N = \frac{E_b}{K\phi} = \frac{208}{2} = 104 \text{ rpm}$$

(ii) $E_b = K\phi \times N = 2 \times 600 = 1200V$

Dynamic braking of DC series motor:-



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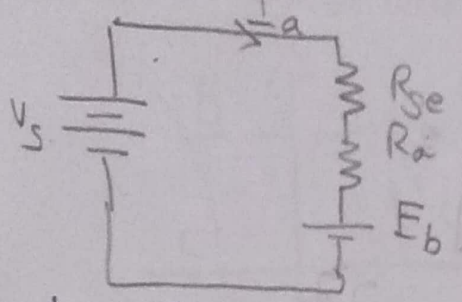
Initially the switch is in 1st pos. where the supply terminals are connected to the armature terminals. Therefore, the machine will act in motoring mode. The equivalent circuit and corresponding arm. current is given by

$$I = \frac{V_s - E_b}{R_a + R_{se}}$$



Substitute $E_b = K\phi \cdot \omega$

Then, $V_s = I_a(R_a + R_{se}) + E_b$.

$$V_s = I_a(R_a + R_{se}) + K\phi\omega$$

W.K.T, $T \propto \phi I_a$

$$T = K\phi . I_a$$

Sub $I_a = \frac{T}{K\phi}$

$$V_s = \frac{T}{K\phi}(R_a + R_{se}) + K\phi . \omega$$

$$\Rightarrow K\phi\omega = V_s - \frac{T}{K\phi}(R_a + R_{se})$$

$$\omega = \frac{V_s}{K\phi} - \frac{T}{K^2\phi^2}(R_a + R_{se}).$$

Now the switch is moved to 2nd pos. There is difficulty in dynamic braking of DC series motor, i.e, the residual flux will cancelled out to overcome that the terminals are interchanged as S_1, S_2. The eq. circuit for braking mode and equation for current is given by for applying the dynamic braking

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The DC supply is disconnected and R_B resistance is connected.

$$\therefore I_a = \frac{E_b}{R_a + R_{se} + R_b}$$

W.K.T, Torque $= K\phi I_a$

For DC series motor, flux $\propto I_a$

$$\phi \propto I_a$$

$$\therefore T = K \cdot I_a^2$$

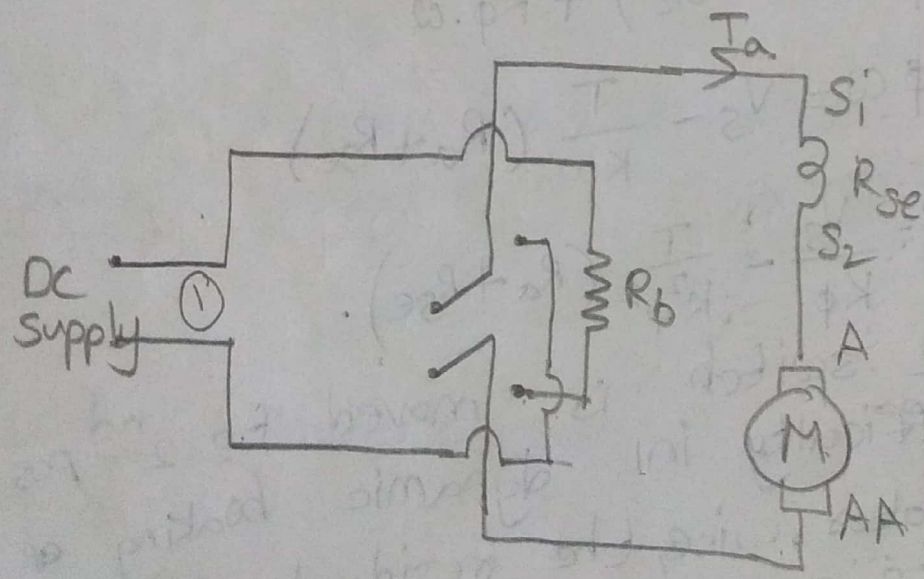
$$T = K \cdot \left[\frac{E_b}{R_a + R_{se} + R_b} \right]^2$$

$$T = K \cdot \left[\frac{K\phi\omega}{R_a + R_{se} + R_b} \right]^2$$

8) Plugging of separately excited DC motor:

For plugging, supply voltage to the armature terminals is reversed such that the armature current will flow in opposite direction.

Let us assume that motor is running at a speed of ω & the operating point is K.



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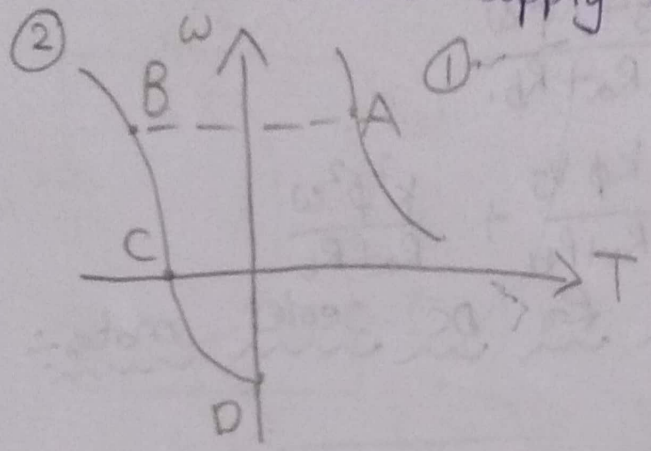
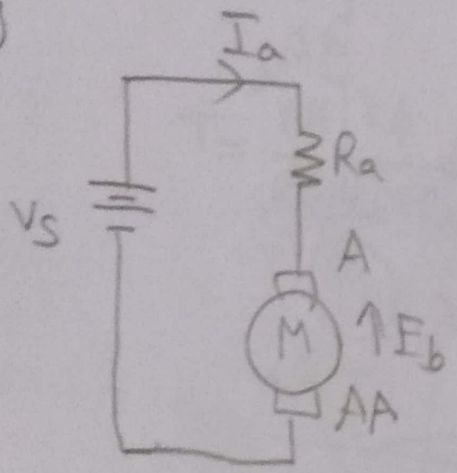
Now the switch is in position. For braking the switch has been moved to 2nd position. The operating point shifts to B. Where electromagnetic torque is in opposite direction to motor rotation and speed decreases to point 'c'. where the speed is zero but the net torque is available which will rotate the motor in reverse direction and the operating point shifts to D when supply is not removed

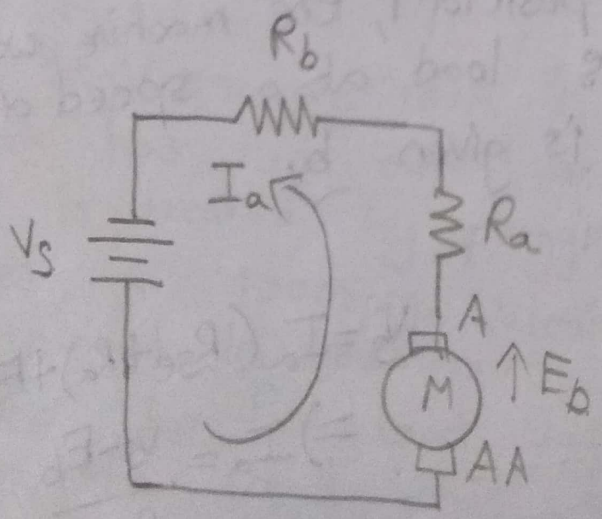


①



$$I_a = \frac{V_s - E_b}{R_a} \quad \text{—①}$$

②



$$I_a = \frac{V_s + E_b}{R_a + R_b} \quad \text{—②}$$

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Sub $E_b = K\phi\omega$

$$T = K\phi I_a$$

$$I_a = \frac{T}{K\phi}$$

$\therefore$ From (2),

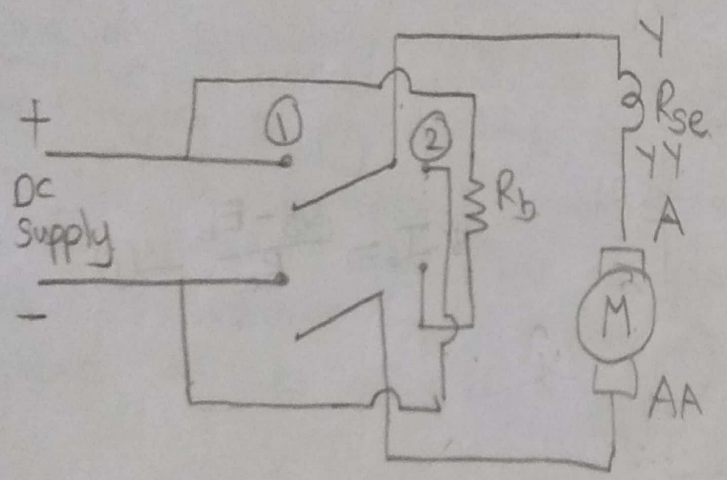
$$I_a = \frac{V_s + E}{R_a + R_b}$$

$$\frac{T}{K\phi} = \frac{V_s + K\phi\omega}{R_a + R_b}$$

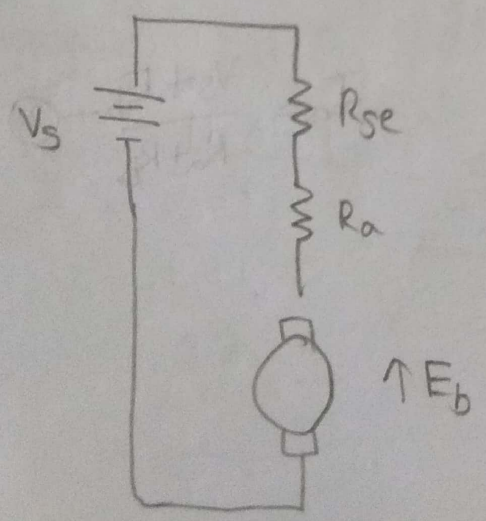
$$\Rightarrow T = \frac{K\phi V_s}{R_a + R_b} + \frac{K^2\phi^2\omega}{R_a + R_b}$$

8

Plugging operation for DC series motor:-



When switch is in position 1, the machine works as a motor driving the load at a speed of ω then the eq. circuit is given by



$$V_s = I_a(R_{se} + R_a) + E_b$$

$$\Rightarrow I_a = \frac{V_s - E_b}{R_a + R_b}.$$

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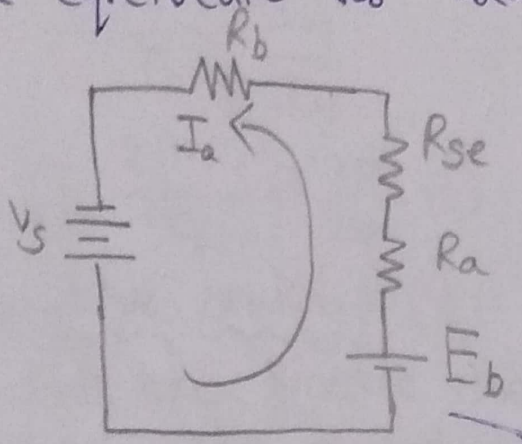
To shift the machine to the braking mode, the switch is turned to position 2, when the current flows from field winding Y & YY and enters the armature terminals.

In plugging operation, there is no necessity to change field terminals as in dynamic breaking.

The eq. circuit for breaking operation



$$V_s + E_b = I_a(R_a + R_{se} + R_b)$$

$$I_a = \frac{V_s + E_b}{R_a + R_{se} + R_b}$$

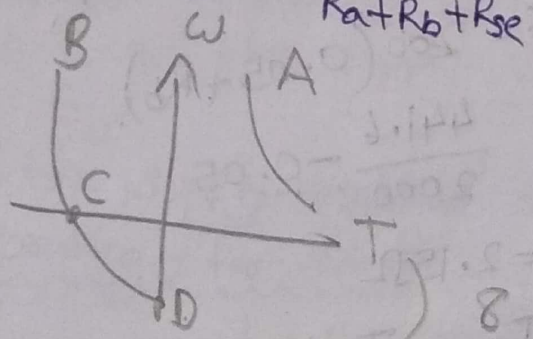
W.K.T $E_b = K\phi\omega$

$T = K\phi I_a$

$\Rightarrow I_a = \frac{T}{K\phi}$

$$\frac{T}{K\phi} = \frac{V_s + K\phi\omega}{R_a + R_b + R_{se}}$$

$$T = \frac{V_s \cdot K\phi}{R_a + R_b + R_{se}} + \frac{K^2\phi^2\omega}{R_a + R_b + R_{se}}$$



*A 220V 970rpm 100A DC separately excited motor has an armature resistance of 0.05Ω It is breaked by plugging from an initial speed of 1000rpm. Calculate (i) resistance to be placed in armature to limit the current twice the full load value. (ii) braking torque when the speed has been fallen to zero

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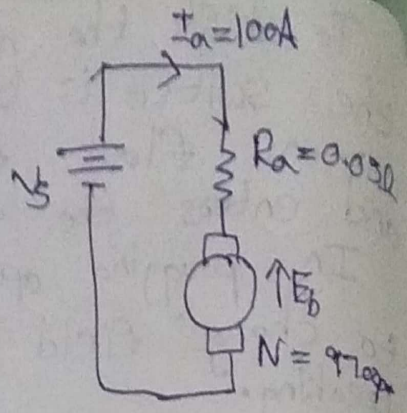
Sol) 970rpm = N_1



$V_s = I_{a_1} R_a + E_{b_1}$

$E_{b_1} = V_s - I_{a_1} R_a$

$E_{b_1} = 220 - 100(0.05)$

$= 215V.$

$N_2 = 1000$ rpm

W.K.T

$E_b \propto N.$

$$\frac{E_{b_1}}{E_{b_2}} = \frac{N_1}{N_2}$$

$$\frac{215}{E_{b_2}} = \frac{970}{1000}$$

$E_{b_2} = 221.6V$

$I_{a_2} = 2 \times 100 = 200A$

$V_s + E_b = I_{a_2}(R_a + R_b)$

$220 + 221.6 = 200(0.05 + R_b).$

$$\Rightarrow R_b = \frac{441.6}{2000} - 0.05$$

$R_b = 2.15\Omega$

$T_1 \propto I_{a_1}$, $T_2 \propto I_{a_2}$.

$P_m = E_b \cdot I_a$

$T_m \cdot \omega = E_b \cdot I_a$

When $N = 0 \Rightarrow E_b = 0$

$$I_a = \frac{V_s + E_b}{R_a + R_b} = \frac{220 + 0}{0.05 + 2.15} = 100A.$$

$T \propto \phi I_a.$

$$\frac{T_1}{T_2} = \frac{I_{a_1}}{I_{a_2}}$$

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$P_m = E_b \cdot I_a$

$T \cdot \omega_m = E_b \cdot I_a \Rightarrow T = \frac{E_b I_a}{\omega}$

$= \frac{221.6 \times 100}{\frac{2\pi \times 1000}{60}} = 211.65 \text{ N-m}$

$\therefore I_{a_2} = 200A, \; T_2 = ?$

$\frac{T_1}{T_2} = \frac{I_{a_1}}{I_{a_2}}$

$\frac{211.65}{T_2} = \frac{100}{200} \Rightarrow T_2 = 423.35 \text{ N-m}$

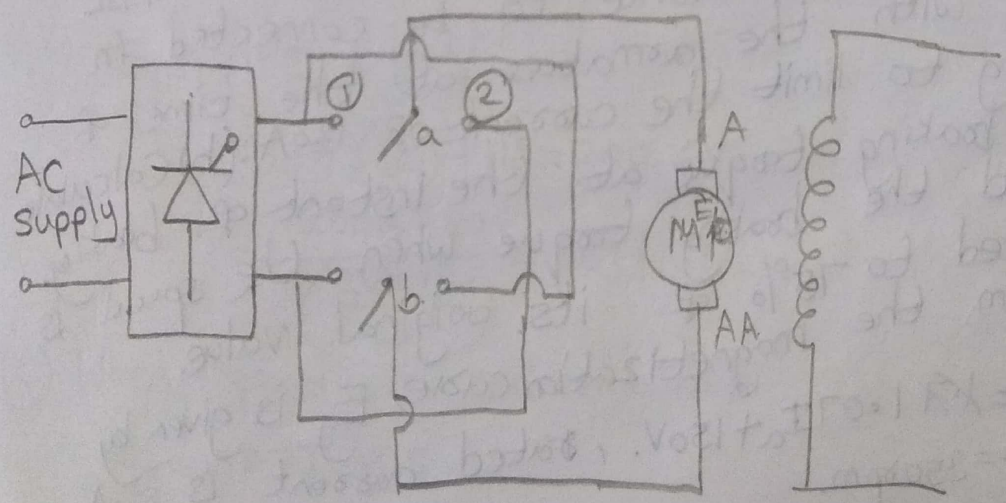
Regenerative braking:-

In this, the kinetic energy of the motor is converted into electrical energy. In this type of braking, the voltage of the DC machine is less than the back emf, such that the machine will be driven into braking mode

To obtain braking mode, the converter is connected across the motor terminals and firing angle is controlled. When $\alpha < 90°$, the supply voltage is greater than E_b.

When $\alpha > 90°$, the supply voltage is less than E_b.

Regenerative braking for separately excited DC motor



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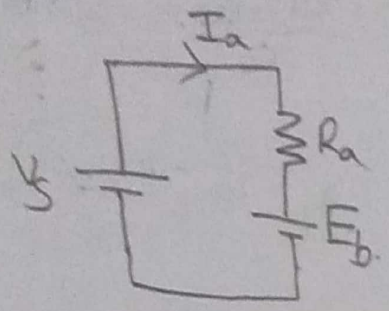
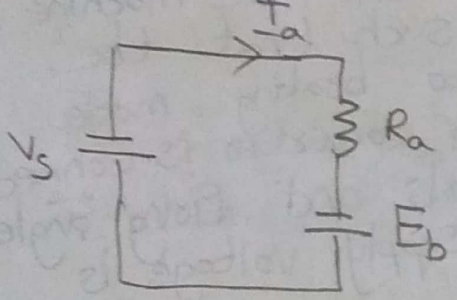
For motoring operation, the switch is in position 1 then the converter acts as rectifier for a firing angle of $\alpha < 90°$. The eq. circuit during motoring operation.



$$I_a = \frac{V_s - E_b}{R_a}$$

When the switch is thrown to 2nd pos, the converter is operated in inversion mode where $\alpha > 90$ then V_s is less than E_b.

Then the eq circuit is



$$I_a = \frac{E_b - V_s}{R_a}$$

* A DC series motor has the following parameters Power $P = 15KW$, $V = 220V$, $R_a = 0.08\Omega$, $R_{se} = 0.17\Omega$. Calculate (a) resistance to be connected in series with the armature at the time of plugging to limit the current of 120A. (b) Calculate the braking torque at the instant of braking. (c) Find the braking torque when the speed is reduced to 75% of its original value.

From the magnetization curve, E_g is given by $E_g = 1.07 I_a + 150V$, rated current is 80A. Speed = 350 rpm.

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Sol) Given data

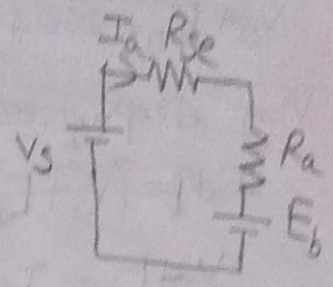
$P = 15\,kW$

$R_a = 0.08\,\Omega$, $R_{se} = 0.17\,\Omega$

$V_s = 220V$

$R_s = 1 \Rightarrow I = 120A$,

$I_a = 80A$, $N = 350\,rpm$.



$$E_b = V_s - I_a(R_a + R_{se})$$

$$E_b = 220 - \overset{80}{\cancel{120}}(0.08 + 0.17)$$

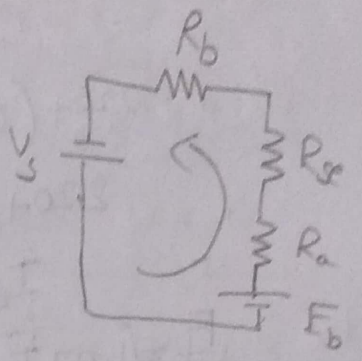
$$E_b = 200V.$$

At the time of plugging, the vtg is $(V_s + E_b)$.

$$= 220 + 200 = 420V.$$

Plugging

$$I_a = \frac{V_s + E_b}{R_a + R_b + R_{se}}$$



$$120 = \frac{220 + 200}{0.08 + R_b + 0.17}$$

$$R_b = 3.25\,\Omega$$

(b) $P_m = T_m \cdot \omega = E_b \cdot I_a$.

$$T_m = \frac{E_b \cdot I_a}{\left(\frac{2\pi N}{60}\right)}$$

$$E_g = 1.07 I_a + 115V$$

$$E_g = 1.07(80) + 115 = 200.6V$$

$$T = \frac{200.6 \times 80}{\left(\frac{2\pi \times 350}{60}\right)} = 437.8\,N\text{-}m$$

(c) When speed is reduced to 75%

$$E_g = 1.07 I_a + 115$$

$N \downarrow \longrightarrow 75\%$ of its rated value

$$E_g = 0.75(1.07 I_a + 115) =$$

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At the time of plugging, the braking voltage is given by

$$V_s + E_b = 220 + [0.75(1.07 I_a + 115)]$$

Vtg drop across braking resistance,

$$\cancel{I_a R_b = (V_s + E_b) - I_a(R_a + R_{se})}$$

$$V_s + E_b = I_a(R_a + R_b + R_{se})$$

$$= I_a(R_a + R_{se}) + I_a R_b$$

$$\cancel{I_a(}$$

$$I_a R_b = (V_s + E_b) - I_a(R_a + R_{se})$$

$$I_a(R_a + R_b + R_{se}) = I_a(0.08 + 3.25 + 0.17)$$

$$= 3.51 I_a$$

$$\therefore 220 + (0.802 I_a) + 86 = 3.5 I_a$$

$$220 + 86 = I_a(\cancel{4.302}\ 2.698)$$

$$I_a = 113.4 A.$$

$$E_b = (1.07 I_a + 115)\,0.75$$

$$= 0.75[(1.07 \times 113.4) + 115] = 177.25 V$$

$$\therefore T = \frac{E_b \cdot I_a}{\omega} = \frac{177.25 \times 113.4}{\left(\frac{2\pi \times 350 \times 0.75}{60}\right)} = 731.2 N\text{-}m$$

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